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Internal shocks in short bursts

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ABSTRACT
The main evidence of the internal-external scenario within the fireball model of GRBs is their high variability. External shocks cannot produce variable bursts and therefore, according to this model, the $\gamma - ray$ emission produced by internal shocks while the afterglow produced by the following external shock. So far the variability was shown only in long bursts (BATSE $T_{90} > 2sec$) . It is not known whether short bursts, which form a different class, are produced in the same way. We have developed an algorithm which is sensitive enough to analyze the temporal structure of short bursts. We analyze a sample of bright short bursts from the BATSE 4B-catalog and find that many short bursts are highly variable ($\delta t_{min}/T \ll 1$, where δt_{min} is the shortest pulse). This indicates that short bursts, like long ones, are produced by internal shocks. We also use the same algorithm to analyze the high resolution (TTE) data of long bursts (only the first 1-2 seconds of each burst). We find that 10ms time-scales are common in long bursts. This result show that long bursts are even more variable then it was thought before ($\delta t_{min}/T \approx 10^{-4} - 10^{-3}$).

Key words: gamma-rays: bursts

1 INTRODUCTION

From the early days of the GRB studies many efforts were invested in classifying the large variety of GRBs into different classes. Until today only one classification is wildly accepted. This is the long/short classification (Kouveliotou et al. 1993, Mao, Narayan & Piran 1994). The main argument for this classification is the bimodal duration histogram of BATSE's archives, but other parameters are supporting this classification as well (Katz & Canel 1996, Kouveliotou et al. 1993). The GRB classes are the long bursts ($T_{90} > 2sec$) and the short bursts ($T_{90} < 2sec$). The temporal features of the long bursts were wildly investigated (e.g. Norris et al. 1996, Norris 1995, Lee et. al. 1995), while there are only few works about short bursts temporal structure. The main reason for this is that short bursts are much harder to analyze (much lower signal to noise ratio in the relevant resolution).

The observations of GRBs afterglow led to a great progress in our understanding of the phenomenon. But there is no observation of an afterglow that followed a short burst. Therefore almost all the deductions from the afterglows' properties are limited to the long bursts. At present the lack of short bursts afterglows can't teach us much as it could be simply due to instrumental limitations.

According to the internal-external GRB model (review Piran 1999) an internal engine ejects a highly relativistic modulated wind. The observed γ-ray emission is a result of internal shocks (collisions between different parts within the wind) (Rees & Meszaros 1994). After the internal collisions the wind still have a relativistic bulk motion that is converted to radiation through an external shock (a collision between the wind and the surrounding matter), this radiation is the observed afterglow (Rees & Meszaros 1992).

The evidences for this scenario is based only on long bursts. The main argument supporting this scenario is the high variability of long bursts. In most long bursts the shortest time scale in the burst (a single pulse duration) is about 10^{-2} of the longest time scale (the whole γ-ray emission duration). External shocks cannot produce such variability efficiently (Sari & Piran 1997), while internal shocks can (Kobayashi, Piran & Sari 1997, Beloborodov 2000). As no variability analysis was made for short bursts, it is not clear if this argument is valid in short bursts as well. An additional argument in favor of the internal-external model is the afterglow and specifically the lack of simple scaling between the GRB and the afterglow. As no short burst afterglow was detected, this argument is not valid for short bursts as well.

We examine here the variability of short bursts and we compare the shortest time scales of long and short bursts. In order to do so we have developed an algorithm that is sensitive enough to find pulses in short bursts. Our algorithm finds the pulses and determine their duration (δt). The burst duration, T, is taken from the beginning of the first pulse till the end of the last one. Using this algorithm we analyze the variability of short bursts. We also analyze the high resolution (TTE) data of long bursts. Unfortunately, TTE data is available only for the first 1-2 seconds of the bursts, so we have only a small fraction of any whole long burst.

We find first, that most short bursts (although not all of them) show a high variability. This result indicates that these short bursts, as well as the long ones, are produced by internal shocks. Second, the shortest time scales in long bursts are similar to these in short bursts. This result is limited to the highest resolution in which we analyzed the long bursts - 5ms. Such time scales were already observed in long bursts (Lee, Bloom & Petrosian 2000), but we show that these time scales are common in long bursts.

In section 2 we describe the data sets we considered for our analysis. The results are brought in section 3 and the conclusions in 4. Our algorithm is described in the appendix.

2 THE DATA SETS

The two BATSE data formats we use are the 64ms concatenate data and the TTE data (see Scargle (1998) for a detailed review). The 64ms concatenate data includes the photon counts of a burst, in a 64ms time bins, from a few seconds before the burst trigger till a few hundred of seconds after the trigger. The concatenate data contains also a very early and a very late data of the burst in a 1024ms resolution. We used only the data in the 64ms resolution. The TTE (Time Tagged Events) data includes the arrival time of each photon in a resolution of $2\mu sec$. This data contains records of only the first 1-2 seconds of the burst. Hence it is usually used only for analyzing short bursts. Both data formats have four energy channels. We used the sum of all the channels (in both formats) that is E > 25Kev.

We have several data sets that we consider in this work. In order to find $\delta t_{min}/T$ in short bursts we consider a sample of short bursts (called *'short'*) and a comparable set of long bursts (called *'long'*). However, the properties of the *'long'* set can't be compared directly with these of the *'short'* set. The long bursts' data is binned in longer time bins then the short bursts data. Therefore two equally intense bursts (one short and one long) would have a different signal-to-noise ratio (S/N). Hence, we need to add noise to the *'long'* set so that it would be comparable to the *'short'* set. The set of long bursts with added noise is called *'noisy long'*. Finally we want to find out the shortest time scale in long bursts. In order to do so we consider a set of long bursts with a good TTE coverage of the first second. This set is called *'high res long'*.

2.1 The *'short'* data set

In the BATSE 4B-catalog there are about 400 records of short bursts, only part of them have good TTE coverage. This is a large statistical sample. But most of these bursts are faint and it is impossible to retrieve their temporal features. There is a trade-off between the sample size, the resolution and the signal to noise ratio. We decided to consider a sample of the brightest 33 short bursts (peak flux in 64ms$>4.37 ph/(sec \cdot cm^2)$) with a good TTE data coverage. In order to get a reasonable signal to noise ratio we have binned this data into 2ms time bins. In this resolution the S/N of the brightest peak in the faintest burst (from our sample) is 4.7. As described in the appendix a peak is significant only if it is more then 4σ above the background, hence this is the largest sample we could consider under the circumstances. The minimal recognized pulse width with this resolution is 4ms.

2.2 The *'long'* data sets

We need a set of long bursts that could be compared to the *'short'* set. The first sample we considered is a sample of 34 long bursts (called *'long'* set) with the same 64ms peak fluxes (one to one) as the bursts in the *'short'* set. This way we prevent differences that arise from different brightness. But, this set couldn't be compared directly with the *'short'* set. Since the highest resolution for these bursts is 64ms, the signal to noise ratio of this set is larger by a factor of $\sqrt{32}$ (assuming the same background level) then the S/N of the *'short'* set (binned into 2ms time bins). To obtain a comparable set we produced another data set (called *'noisy long' set)* out of the *'long'* set by treating this set as if the basic time bin was 2ms and adding a Poisson noise accordingly. This procedure reduces the signal to noise ratio and made this set comparable to the *'short'* set.

We used the *'noisy long'* set also as a test to our algorithm. By analyzing the *'noisy long'* set we can learn how good is our algorithm in retrieving the attributes of the *'long'* set . We also can learn how does the noise influence the analyzed temporal structure. In this way we can try to estimate what was the original temporal structure of the *'short'* set.

2.3 High-resolution long bursts

The comparison between the shortest time scales in long and short burst requires the analysis of high-resolution long bursts. The only data type with high enough resolution is TTE data, but this data is available only for the first 1-2sec of the bursts. We have searched for long bursts that begin with a bright enough pulse during the first two seconds. We also demanded that the counts would drop back to the background level during this time, so the beginning of the light curve will not be dominated by a pulse longer then 2sec. We found 15 such bursts with good data called *'high res long'* set. We compared the first 1-2sec of these bursts with 15 short bursts with comparable peak fluxes (taken out of the *'short'* set). The analysis of both groups is done in 5ms time bins.

3 RESULTS

3.1 Long bursts pulses attributes

We analyzed the *'long'* set and found the duration, T, and the shortest pulse duration, δt_{min}, of the bursts. Figure 1 show $\delta t_{min}/T$ and δt_{min} as a function of T. Figure 1a shows that δt_{min} and T are not correlated. Consequently, $\delta t_{min}/T$ is smaller for longer durations. The value of $\delta t_{min}/T$ for the longer bursts are $10^{-3} - 10^{-2}$. The grey areas are restricted because of the resolution. We see that δt_{min} is limited by the resolution, suggesting even higher variability.

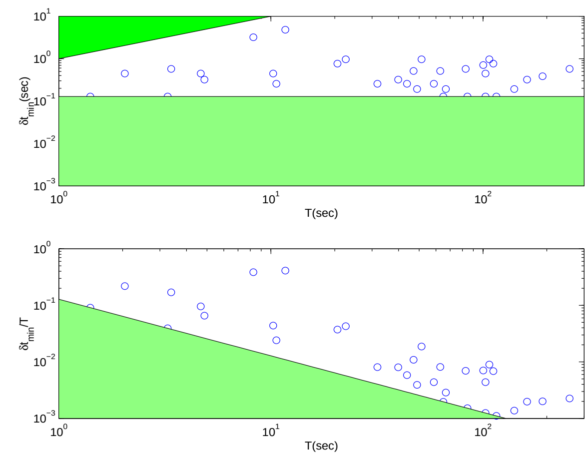

Figure 1. a) $\delta t_{min}/T$ and b) δt_{min} as a function of the burst duration T in long bursts. The gray areas are not allowed because of the resolution ($\delta t > 128ms$) or the parameters definition ($\delta t < T$)

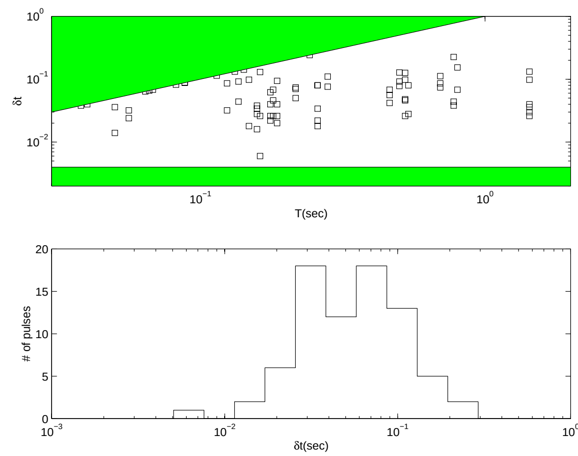

Figure 3. Top (a): The pulse widths in all the short bursts as a function of T. The gray areas are not allowed because of the resolution ($\delta t > 4ms$) or the parameters definition ($\delta t < T$).**Bottom (b)**: The histogram of the pulse width in short bursts.

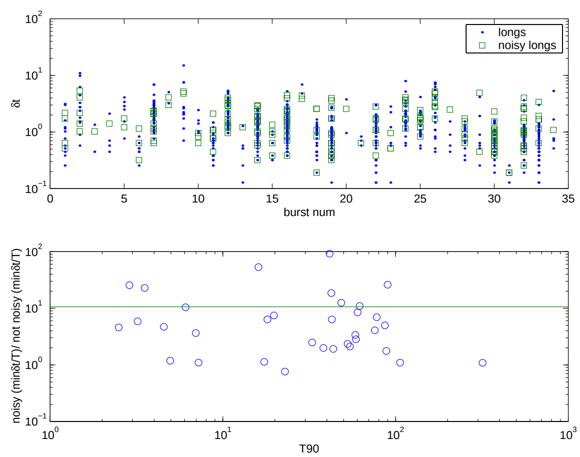

Figure 2. Top (a) : All the pulses width found in the *'long'* and *'noisy long'* samples. **Bottom (b)** : The ratio between $\delta t_{min}/T$ in the *'long'* and *'noisy long'*, as a function of BATSE T_{90}.

3.2 *'Noisy Long'* VS Long bursts

Before analyzing the short bursts we studied the effect of noise on the time profile. We do so by comparing the attributes of the *'long'* set with these of the *'noisy long'* set *(see 2.2)*. This procedure also tests our algorithm. Since we know the original signal (in the *'long'* data set) we can find out the efficiency of the algorithm in retrieving the *'long'* set attributes out of the *'noisy long'* set.

Figure 2a represent all the pulses found in the *'long'* and *'noisy long'* samples. We can see that the algorithm retrieve the main features of the bursts out of the noisy sample, but there are some effects of the noise. One effect is that many pulses are 'lost' because of the noise (only 30% of the *'long'* pulses are found in the *'noisy'* set). This is as a result of two effects: a) some pulses are too weak to be distinguished from the amplified noise. b) Some pulses merge with other pulses because the gap between them is of the same order of the noise. The first effect shouldn't change the width of the found pulses, but the second one causes pulse widening. So we expect fewer pulses and a shift toward wide pulses in the noisy sample. Both effects are seen clearly in Figure 2. In the noisy sample there are 203 pulses with an average width of 1.62sec while in the *'long'* sample there are 695 pulses with an average width of 1.39sec.

Another important issue is the effect of the noise on the parameter $\delta t_{min}/T$. This parameter is affected by the pulse widening as well as by the reduction in the bursts duration. The burst duration becomes shorter, because of the noise, if the first or the last pulses of the burst are lost. Figure 2b show the effect of the noise on $\delta t_{min}/T$. We can see that the noise increases it by a factor of 10 in average.

3.3 Pulses attributes of short bursts (compared with the *'noisy long'*)

As already mentioned the same algorithm was applied to the *'short'* data set. In Fig 3a all the pulses widths are shown as a function of the burst duration. The gray areas are not allowed because of the resolution ($\delta t > 4ms$) or the parameters definition ($\delta t < T$). Fig 3b is the distribution of the pulses width (δt). One can see that δt is about 50-100 ms without a strong correlation with T.

These pulse widths are only upper limits. First, the noise causes the pulses to seem wider (see 3.2) by a factor of few. Second, the resolution is limited. It is likely that the shortest pulses in the *'short'* set are shorter then the best highest resolution of our data. Fig 3b shows a histogram that begins with pulses at 12ms (except for one very bright and short pulse of 6ms), which is only three times of best resolution. This is also the case with the *'noisy long'* set - the shortest pulse in this set is about 400ms which is three times the best resolution, while the shortest pulse of the *'long'* set begin at the resolution limit (128ms). Indication for very short time scales in short bursts was already found (Scargle, Norris & Bonnel 1997). 25% of the bursts in the *'short'* set contain time scales of less then 20ms.

Fig 4 show δt_{min} and $\delta t_{min}/T$ in both groups *'short'* and *'noisy long'*. In the *'short'* set the median $\delta t_{min}/T$ is 0.25 while 35% of bursts have $\delta t_{min}/T < 0.1$ and 35% of the

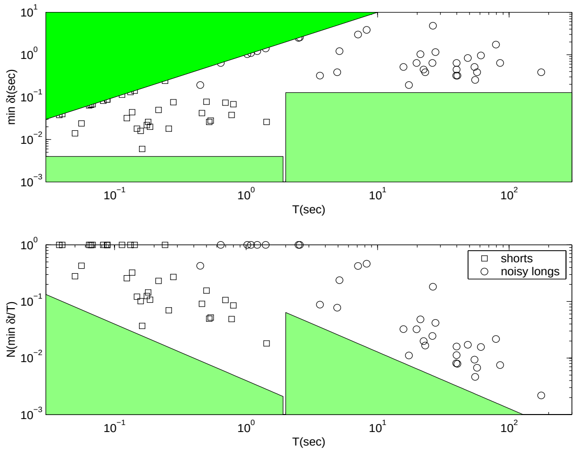

Figure 4. a,b)The shortest time scale observed in any burst (the shortest pulse-δt_{min}) represented as a function of the total duration of the burst. The data sets represented here are the shorts and the noisy longs. The shaded areas are excluded because of the data resolution (4ms for shorts and 128ms for noisy longs) or the data definition ($\delta t_{min} < T$).

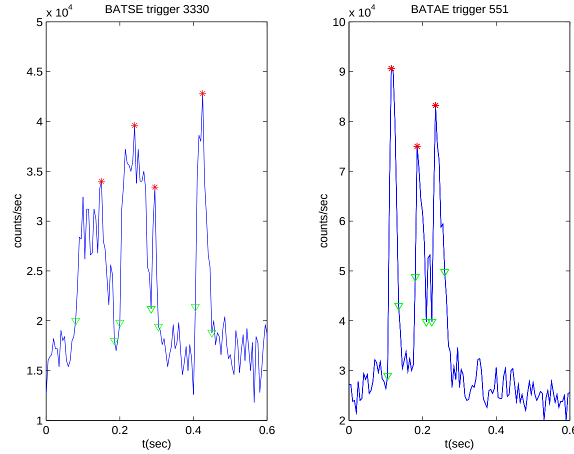

Figure 5. Left) The beginning of BATSE trigger 3330 (a long bright burst with $T_{90} = 62sec$). **Right**) The whole light curve of BATSE trigger 551 (a bright short burst with $T_{90} = 0.25sec$). The peaks found by our algorithm marked by stars. The triangles mark the pulses width. The figure shows that the short time scales in these bursts are similar (at least at resolution of 5ms).

bursts show a smooth structure ($\delta t_{min}/T = 1$). This result could mislead us to the conclusion that a significant fraction of the short bursts have a smooth time profile. But a look at the *'noisy long'* results show that also in this group more than 20% of the bursts are single pulsed while there were no such bursts in the original *'long'* set. Naturally, the bursts that loose the fine structure because of the noise are bursts with fewer original pulses. It is clear that short bursts have less pulses then long ones so they are more '"vulnerable" to the noise. Hence we must conclude that the majority of the short bursts are very variable ($\delta t_{min}/T \ll 1$).

3.4 High resolution long bursts vs. short bursts

We compared the time profile of the first seconds of 15 long bursts with the time profiles of 15 short bursts. Figure 5 shows the light curves of a short burst and the first second of a long burst. The time scales of both bursts are quite similar.

Figure 6 shows the pulse widths histogram of the beginning of long bursts vs. the same histogram of the short bursts. The time scales in both samples are quite similar in the range of 10-200ms, while the long bursts have additional pulses in the range of 0.2-1sec. Long bursts contain, of course, longer pulses, but in the sample we considered we demanded that the counts would fall back to the background level within the first second. In this way we have limited the pulses width of the long bursts. Both histograms begin at 10-20ms, which is at the limit of the pulse width resolution (10ms). It is very likely that both samples contain shorter time scales that cannot be resolved. Walker, Schaefer & Fenimore (2000) performed similar analysis of TTE data in 14 long bursts. They found only one long burst with very short time scales. The difference between the results is because of the different samples considered. Walker et al. (2000) considered the bursts with the maximal total photon counts within the TTE burst recored, while we demanded that the

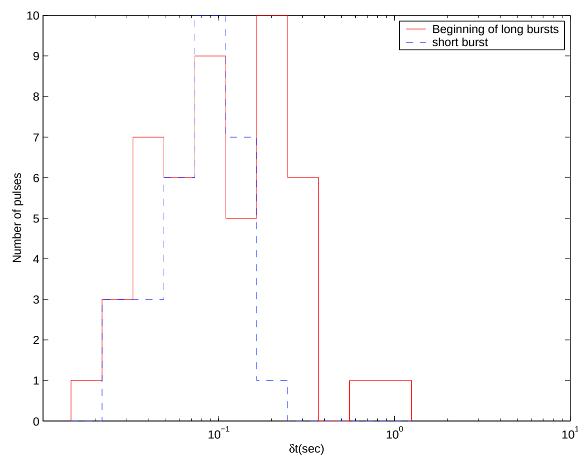

Figure 6. Smooth line) The histogram of pluses width in the beginning (first 1-2 seconds) of long bursts. **Dashed line)** The histogram of pluses width in short bursts. Both samples time-bin size is 5ms.

counts will return close to the background level within the TTE recored. Most of the bursts in Walker et al. (2000) sample are dominated by a long and bright pulse. Walker et al. (2000) also make a wavelet analysis (in which they are not looking for separate pulses but for intrinsic time scales), and in this analysis their results are in agreement with ours.

Finally we have to remember that a sample of 15 bursts is rather small but it is enough to show that time scales of a few tens of msec are common even in long bursts. The part of the long bursts that we have analyzed is very similar to a complete short burst. Even though the sample is small and the bursts were not chosen randomly, this similarity is not a result of the way the sample was selected. This is because the way we selected the sample gave no restriction on the structure of the light curves in time scales shorter then 1sec.

This similarity raises the question whether it's possible

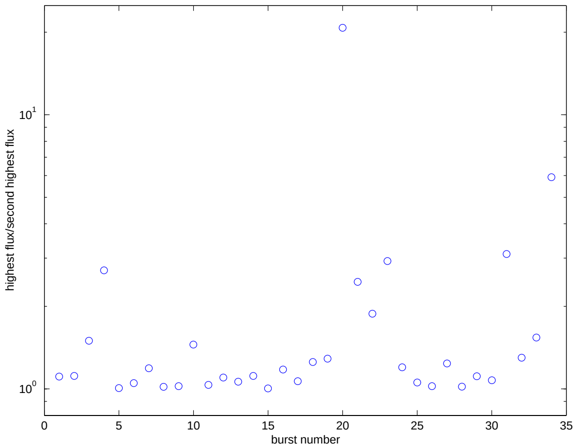

Figure 7. The ratio of the flux in the brightest peak and the second brightest peak in long bursts.

that short bursts are actually only a small fraction, which is above the background noise, of long bursts. We have already seen that the noise cause us to loose pulses. Is it possible that a long burst with a single dominant, very intense pulse, (or a group of very close and intense pulses) will loose all its structure, apart for this intense pulse, due to noise and become a short burst. Figure 7 rule out this option. It depicts the counts ratio between the most intense and the second most intense pulses within long bursts. The graph shows that almost in all bursts (around 80%) the two most intense peaks are at the same level. It means that there is no way that noise can cause one pulse to disappear without the other. As these two peaks in each burst are well separated in time, there is no way that noise can convert significant fraction of long bursts into short ones. In very few cases we managed to add noise and convert a long burst into a short one. It means that noise could have some effect on the duration histogram but it certainly cannot produce the observed bimodality.

4 CONCLUSIONS

Our main result is that $\delta t_{min}/T \ll 1$ for most short bursts as well as for long bursts. As external shocks cannot produce such a temporal structure, this result indicates that most short bursts are produced in internal shocks. In 30% of the short bursts the observed δt_{min} is the same as the observed duration - $\delta t_{min} \approx T$. However, a comparison with the *'noisy long'* set, shows that this feature is quite likely to be an artifact of the noise.

As the short bursts are produced in internal shocks, the expanding wind still have a high Lorentz factor at the end of the internal shocks. This bulk motion should slow down by the surrounding medium (if it's dense enough); this deceleration would emit an afterglow. Therefore we predict that afterglows would be observed in the future following short bursts. These afterglows should have no simple extrapolation to the γ-ray emission.

A second result is that short time scales (10ms or less) are common in long bursts. Hence, $\delta t_{min}/T \approx 10^{-4} - 10^{-3}$ in many long bursts. This result make it very difficult to explain the high variability in any other way but the internal shocks (e.g. high inhomogeneity in the ISM).

Appendix -The algorithm

Our algorithm finds the peaks of the bursts. Each peak corresponds to a single pulse; a pulse is the basic event of the light curve. The algorithm is based on the algorithm suggested by Li & Fenimore (1996). Li & Fenimore define a time bin t_p (with count C_p) as a peak if there are two time bins $t_1 < t_p < t_2$ (with counts C_1, C_2 respectively) which satisfies a) $C_p - C_{1,2} > N_{var}\sqrt{C_p}$ and b) C_p is the maximal count between t_1 and t_2. N_{var} is a parameter that determines the significance of the peak.

There are two problems with this algorithm. First, this algorithm analyzes only data in a single time resolution (fixed time bin size). Therefore the algorithm looses long and faint pulses. A peak that does not satisfy the criterion described above in the raw data resolution could satisfy the criterion if the data resolution is lower (longer time-bins). This algorithm would miss such a pulse. Second, N_{var} determines the trade-off between sensitivity and false peaks identification rate. When N_{var} is low the algorithm finds false peaks as a result of the Poisson noise. When N_{var} is high the algorithm misses real peaks. Finding false peaks is a severe problem during long periods of constant level Poisson noise, like the background (as will be explained shortly). Long bursts contain such periods (periods of only background noise). These periods are called quiescent times. In order to avoid false peaks in long bursts $\mathrm{N_{var}}$ must be large(≥ 7), which means an insensitive algorithm. Short bursts contain less quiescent times, and of course shorter ones. But, short bursts contain much less pulses then long burst (three to four compared to an average of more than thirty) and much smaller S/N. Finding even one false peak could change the features of the burst drastically. Too insensitive algorithm could loose all the burst structure. In order to avoid false peaks in short bursts $\mathrm{N_{var}}$ must be at least as large as 5. As described in section 2.1, the S/N in some of the bright short bursts is smaller then 5. Such N_{var} will prevent the algorithm from finding even one peak in these bursts.

We solved the first problem by analyzing the data in different resolutions. The results of the algorithm in different resolutions are merged into a single set of peaks. We solved the second problem by restricting the search for peaks only to 'Active Periods'. Active periods are periods with counts that correspond to source activity (we will define it later on).

There are few advantages for analyzing only active periods. The main one is that a lower N_{var} can be used during these periods with smaller risk of finding false peaks. The risk of finding false peaks due to a Poisson noise depends on the time scale in which the original signal (i.e. without the noise) changes its counts rate in the same order as the Poisson noise level. If the signal is constant (no real pulses), then this time scale is as long as the signal. If the constant signal is longer, it contains more time bins with the same level of Poisson noise counts. Hence, there is a larger chance of finding within these time-bins three time-bins, t_p, t_1 and t_2, that satisfy the criterion in Li & Fenimore algorithm. Then t_p would become a false peak. On the other hand, if

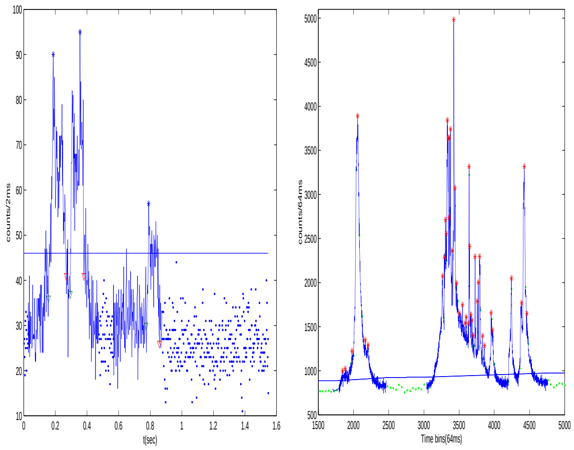

Figure 8. Left) Time profile of BATSE trigger 2952 (bright short burst). Right)Time profile of BATSE trigger 2156 (bright long burst). The solid line marks the active periods. The horizontal line marks the activity level. All the time bins with counts above the activity level are 'active bins'. The peaks are marked by '*'.

the signal is changing monotonically then the length of the signal is irrelevant. t_p, t_1 and t_2 must be within the period in which the signal changes at the same order as the Poisson noise level; there is no chance of finding t_2 with C_2 significantly below C_p (if the signal is rising) out of this period. During the active periods the signal is changing rapidly (usually on time scales of seconds or less), and the Poisson noise is superimposed on steep slopes. In this case a false peak could only be found during the period in which the signal didn't change compared to the noise level. There are much less time bins during this period and hence there are much less chance of finding false peaks.

The second advantage is that when an active period is found we almost certain that it is a part of the burst. This is important since one false peak in the 'wrong' place (for example hundred of seconds after the burst ended) can change the burst properties drastically. By analyzing only active periods we can use smaller N_{var} (=4) and get a more sensitive and accurate algorithm.

Our algorithm works in several steps. First, it determines the background level of the signal (as a function of time). Then it finds an activity level, demanding a probability of 0.9 (per burst) that all the time bins with counts above this level (called 'active bins') correspond to source activity and not of the background Poisson noise (we demand that on every ten bursts there is, on average, a single false 'active bin'). The Activity level depends on the background and its value is between 4σ to 5σ above the background. From each active bin we search to the right and to the left until the count level drops to the background level on both sides. We call all these bins together an active period (from the time bin that the counts are above the background until the time bin that the counts reaches the background level again). In most cases a single active period includes many active bins and a burst may contain more then a single active period (see Fig 8). Note that if the algorithm misses an active period in one resolution, it can still find it in a different (lower) resolution, in which the noise level is lower.

Once the active periods of a given burst have been determined we apply the Li & Fenimore algorithm to the active periods (using Nvar=4) and determine the peaks. We repeat this procedure (finding the active periods and the corresponding peaks), several times for different time resolution. To obtain lower resolution data we convolve the original signal (in the basic time bins) with a Gaussian, whose width determines the resolution. Finally, after finding the peaks in different resolutions we merge those sets of peaks to a single set (requiring that a peak must appear in at least two different resolutions). The merge is done by merging the highest resolution set with the second highest one and then taking this merged set and merging it with the third highest resolution set and so on. On different resolutions the same peak could be found on different time bins. In each case two peaks on different resolutions are considered as a single one if the peak in one resolution falls between t_1 and t_2 of the peak in the other resolution.

Each peak corresponds, of course, to a pulse. The pulse width (δt) is defined by two points (on each side of the peak) that are higher than the background by 1/4 of the peaks height or by the minimum between two neighboring peaks (if the latter is higher). The duration (T) of the burst is the time elapsed from the beginning of the first pulse till the end of the last pulse (so in single pulsed burst $T = \delta t$).

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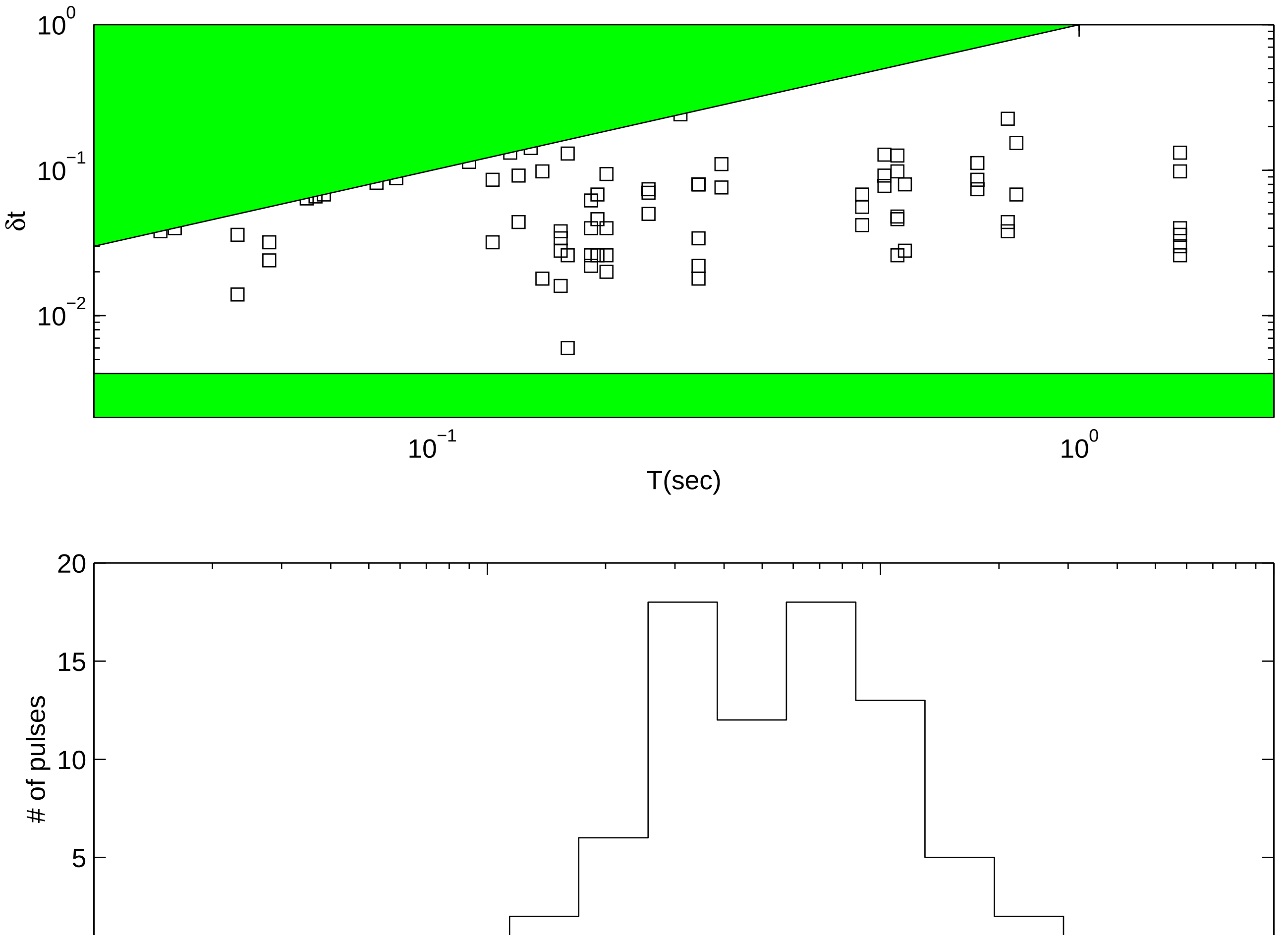
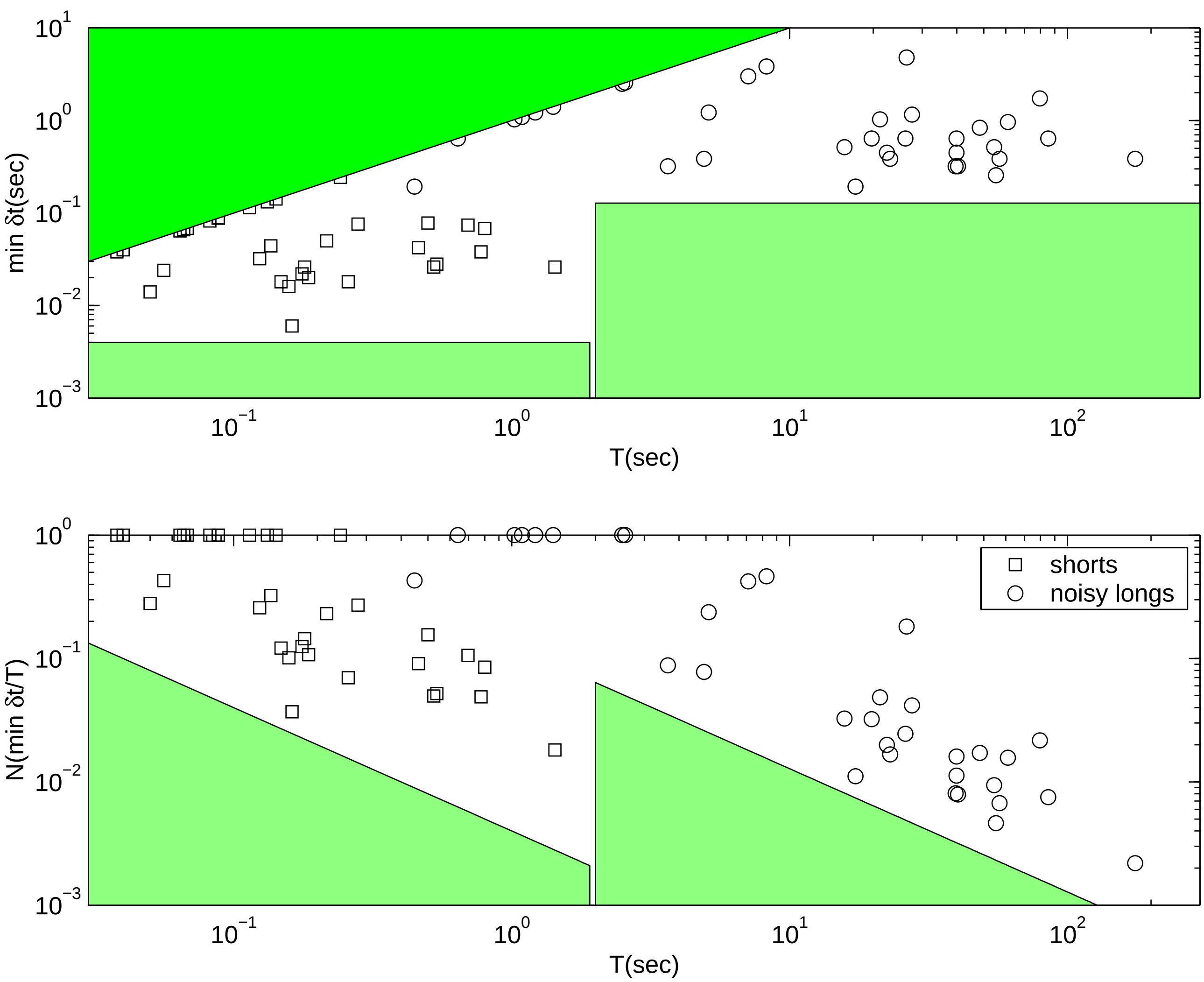


10^0
10^{-1}
10^{-2}
δt
10^{-1}
10^0
T(sec)
20
15
10
5
0
# of pulses
10^{-3}
10^{-2}
10^{-1}
10^0
δt(sec)



min δt(sec)
T(sec)
N(min δt/T)
T(sec)
shorts
noisy longs